Energy Storage Comparison Analysis with Gas-Fueled Technologies

Prepared for
Energy Solutions Center

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Executive Summary

As more variable renewable energy generation is incorporated into electric grids across the country, energy storage solutions will be required to respond to both short- and long-duration energy requirements. Lithium-ion batteries and other energy storage technologies will play a prominent role in providing some of these needs, but other fuel-based technologies could potentially be deployed in the same use cases, providing similar functionality.

ICF assembled cost and performance information for several technologies that can perform energy storage functions, grouped into short and long-duration storage technologies. Gas-fueled technologies that can perform both short- and long-duration storage functions were also included. Future outlooks for cost and performance improvements showed significant cost reductions ahead for lithium-ion batteries, but not other technologies.

A cost comparison for the energy storage technologies is shown in Table 1. The “fuel cost to operate” estimates use 2019 EIA U.S. average industrial electricity and natural gas prices, combined with the range of system efficiencies, to estimate the cost to produce a kilowatt-hour of electricity. The Fuel Cost to Operate will vary depending on local electricity or gas prices, and whether or not the electricity can be obtained from excess renewable generation.

Table 1. Cost Comparison for Energy Storage Technologies

Technology	Primary Application	Capital Costs ($/kW)	O&M Costs ($/kW-year)	Fuel Cost to Operate ($/kWh)
Short-Duration Technologies				
Flywheel Energy Storage	Small-scale frequency and voltage stabilization	$2,000 – 4,000	$10 – 20	$0.08 – 0.10
Lithium-Ion Battery 2020	Small-to-large demand response, ancillary services, frequency/ voltage stabilization	$900 – 1,700	$10 – 20	$0.08 – 0.09
Lithium-Ion Battery 2030		$450 – 900	$5 – 10	$0.08 – 0.09
Long-Duration Technologies				
Redox Flow Battery	Industrial-scale peak shaving, frequency/ voltage stabilization	$1,400 – 1,600	$10 – 12	$0.08 – 0.11
Compressed Air to Power	Utility-scale baseload generation and peak shaving	$1,000 – 1,200	$16 – 18	$0.09 – 0.17
Pumped Hydro-electric Storage	Utility-scale baseload generation and peak shaving	$1,500 – 1,700	$13 – 17	$0.08 – 0.09
Gas-Fueled Technologies				
Industrial CHP	Industrial-scale demand response, spinning reserve	$1,200 – 1,800	$30-$45/kW-year, ~$10/MWh	$0.015 – 0.020
Modular Gas Engines	Demand response, spinning reserve, balancing renewables	$1,300 – 1,800	$35/kW-year, ~$6/MWh	$0.03 – 0.05
Power-to-Gas Fuel Cell	Convert excess electricity to hydrogen for time shifting	$2,900 – 5,600	$30 – 40/kW-year, plus stack replacement	$0.03 – 0.04

As shown in the comparison analysis, gas-fueled technologies are currently cost-competitive with other storage solutions. Moving forward, utilities and grid operators will need to determine which energy storage solutions will most cost-effectively meet their needs, while also weighing other factors like environmental goals and resiliency requirements for critical loads. In some cases, gas-fueled engines, turbines, and fuel cells may be able to provide many of the same functions as energy storage, in a way that provides benefits to both utilities and their customers.

In order to compare total system costs, ICF assembled a 20-year life cycle cost comparison across all technologies using average values. We assume that equipment is installed in 2020, operating through 2040, at 2,000 full load equivalent hours of discharge/generation each year. Total estimated costs are assembled for each technology in 2020 dollars, using average U.S. industrial electricity and natural gas prices to calculate effective fuel costs. The results are shown in Figure 1.

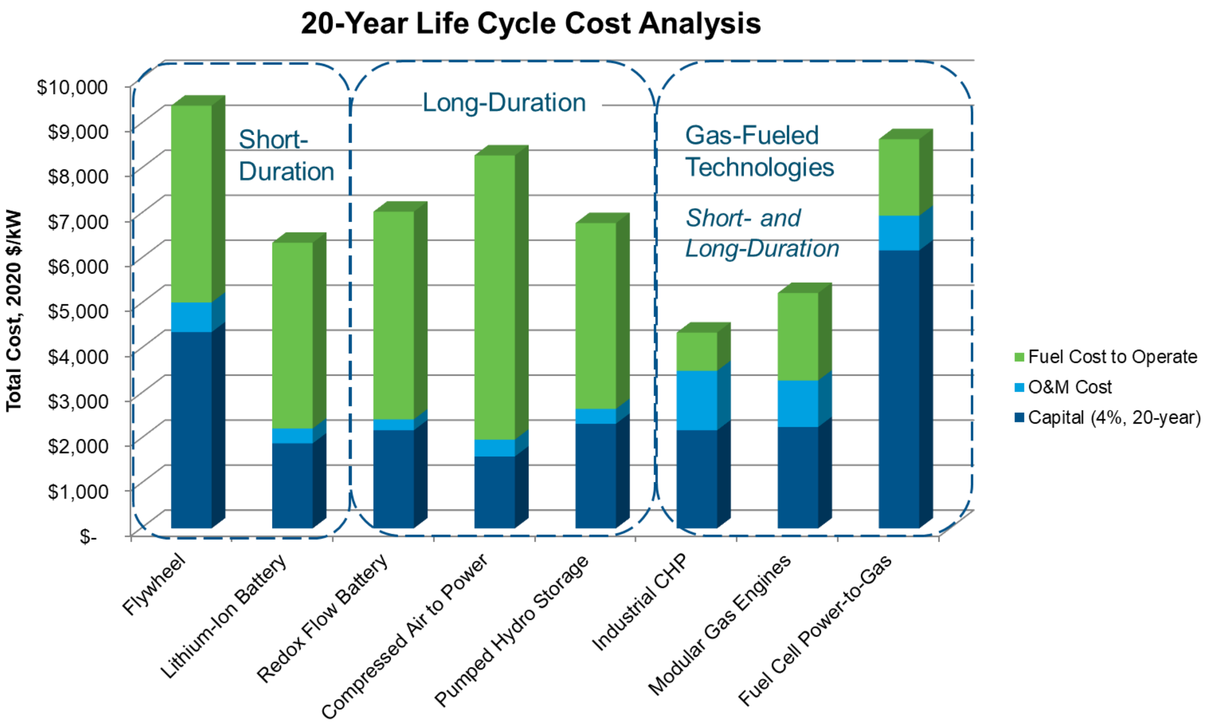

Figure 1. 20-Year Life Cycle Cost Comparison for Energy Storage and Gas-Fueled Technologies

From the analysis, Flywheels and Fuel Cell Power-to-Gas options represent the highest cost options, while opportunities for Compressed Air and Pumped Hydro were found to be limited. Thus, Lithium-ion batteries are the most promising technology for short-duration applications and Redox Flow Batteries are the most promising for long-duration storage requirements. However, gas-fueled technologies that can fill many of the same roles are often overlooked when planning for new renewable capacity.

In cases where industrial CHP or modular gas engines can be utilized, they are likely to be more cost effective than Lithium-Ion or Redox Flow Batteries over a 20-year period, depending on storage requirements, local fuel costs, and available electricity markets.

1 Introduction

As decarbonization efforts in the electric power sector continue to proliferate and increase the amount of variable renewable energy generation on the grid, energy storage technologies will be required to respond to variable generation and provide services to the grid. Some forms of energy storage can provide transient response to hourly load variations from PV or wind output, and others can provide longer-term generation to account for grid deficiencies that could last hours or even days if resources are unable to meet demand.

Currently, the majority of energy storage deployed in the U.S. and around the world is pumped hydroelectric storage, with the ability to typically provide more than 8 hours of reliable power for peaking requirements. However, the last pumped storage project installed in the U.S. was in the 1980's, with few projects being considered in the development pipeline.

Battery storage technologies – most notably lithium-ion – also provide benefits to renewable integration with their ability to manage grid variability. As battery storage costs continue to decline, they are being increasingly called upon to provide short duration frequency regulation and load following services given the rise of intermittent power generation.

Under future grid scenarios in which variable renewable generation reaches high levels, energy storage technologies will need to provide significantly higher levels of both short- and long-term storage than they are required to today. While battery technologies continue to decline in cost, the ability to provide significant levels of long-term storage in a high renewable environment may not meet future demand, and pumped storage projects have experienced little-to-no growth in recent years. Given the future requirements for balancing intermittent generation, there will likely be a high need for additional storage options or technologies, such as increased thermal energy storage and fuel-based options.

Gas-fueled technologies can be a cost-effective option for the balancing of large-scale intermittent renewable generation in the future. Traditional inertia-based machines, when configured properly, have the ability to quickly provide synchronous generation and transient response when called upon by the grid. These technologies can provide grid services for extended periods of time at a relatively low cost.

The following summary of technologies provides a useful means of comparing various traditional energy storage and gas-fueled technologies in terms of capabilities, performance, and cost. Future advancements and cost reductions from 2020 to 2030 were considered for each technology, but lithium-ion battery systems are the only technology expected to significantly change over the course of the decade.

This study is not intended to be taken as a comprehensive analysis of all potential energy storage technologies, but rather a summary of the current status and future outlook for the most commonly deployed energy storage solutions, compared to the capabilities of gas-fueled technologies that can potentially fill the same roles.

2 Energy Storage Technology Overview

Energy storage technologies are generally grouped into short-duration (<4-hour) and long-duration (>4-hour) variants, serving different types of applications. Short duration technologies like flywheels and lithium-ion batteries are used to provide fast response in frequency regulation markets, or energy price arbitrage to strategically charge and discharge based on market price signals on a daily basis. Long duration technologies are more typically used in utility-scale applications to provide a flexible a source of long-term power output for the grid during periods of high demand.

Gas-fueled technologies like industrial combined heat and power (CHP), engine power plants, and fuel cells could potentially provide viable solutions for both short- and long-duration storage applications. Table 2 provides an overview of the energy storage technologies assessed in this study.

Table 2. Energy Storage Comparison - Technology Overview

Energy Storage Technology	Discharge Duration	Roundtrip Efficiency	Dispatch Response Time
Short-Duration Technologies			
Flywheel Energy Storage	minutes / hours	70 – 90%	Milliseconds
Lithium-Ion Battery Storage	1 – 4 hours	~85%	Milliseconds
Long-Duration Technologies			
Redox Flow Battery	4 – 12 hours	65 – 85%	Milliseconds
Compressed Air to Power (CAES)	4 – 12 hours	41 – 75%	5-15 minutes
Pumped Hydroelectric Storage	>10 hours	76 – 85%	Seconds to Minutes
Gas-Fueled Technologies			
Industrial CHP	>24 hours	70 – 80% (total CHP efficiency, HHV)	Milliseconds to Seconds
Modular Gas Engines	>24 hours	36 – 42%(electrical efficiency, HHV)	Milliseconds to Minutes
Power-to-Gas Fuel Cell	>24 hours	34 – 51% (electrical efficiency, HHV)	Seconds to Minutes

3 Short Duration Energy Storage Technologies

Short-duration storage technologies can only provide energy for up to 2-4 hours before they need to recharge, which places some limits on their functionality, but they can make up for this with other advantages.

3.1 Flywheel Energy Storage

Flywheel energy storage systems use kinetic energy stored in a rotating mass. Power inputted to the system accelerates the mass via an integrated motor-generator. The kinetic energy of the rotating mass is expended via the same motor-generator to output power. Figure 2 highlights the different components of a flywheel energy storage system.[1] Flywheel technology is proven to be effective for specific applications that require near instant dispatch response time and several cycles per day. Flywheels have been employed as energy storage for over a hundred years and have seen increased usage in the past decade due to falling costs of several key components, such as the motor drive power electronics. However, flywheels are thought to be nearing price maturity and deployment is now largely dependent on the price of other competing technologies. There are several projects slated for installation this year.

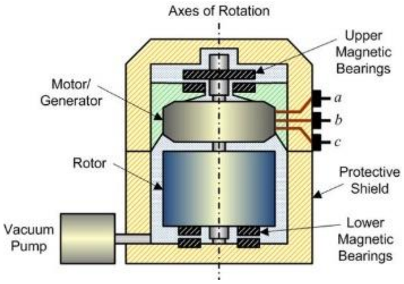

Figure 2. Flywheel Energy Storage Diagram

Flywheel Energy Storage: Cost & Performance Specifications	
Discharge Duration	minutes – 2 hours
Capital Costs ($/kW; $/kWh)	$2,000 – 4,000; $10,000 – $15,000
O&M Costs ($/kW-year)	$10 - 20
Fuel Cost to Operate ($/kWh-year)	$0.08 - 0.10
Energy Capacity (based on existing installations)	Up to 5 MWh
Power Capability (based on existing installations)	>10 MW
Expected Life	100,000 cycles
Roundtrip Efficiency	70 - 90% (friction contributes to efficiency losses)
Energy Density (Wh/kg)	20 – 80
Power Density (W/kg)	~5,000
Dispatch Response Time	< 4 milliseconds
Technology Applications	Grid frequency and voltage stabilization Uninterruptable power supply (UPS)
Technology Drawbacks	40 – 100% energy capacity loss / 24 hours
Example Projects	Stephentown, NJ (20 MW)

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[1] https://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications

3.2 Lithium-Ion Battery (Li-Ion)

Li-Ion batteries store energy via electro-chemical potential. Lithium ions move through an electrolyte from the anode to the cathode when discharging, and vice-versa when charging, as show in Figure 3.[2] This storage technology has seen substantial market penetration for electric vehicles and stationary storage applications in recent years with several high-profile installations and significant price reduction. Capital costs are primarily driven by the battery module cost in the system, which utilize similar technology to that utilized in the eletcric vehicle industry. Operating costs tend to driven by energy capacity augmentation requirements given the 1.5% to 3% per year degradation rate of lithium-ion batteries. Growth in both industries over the last several years has yielded cost reductions that benefit lithium-ion battery systems. Battery modules have observed reduction of approxiamtely 87% since 2010, expected to drop to $50-$60/kWh in 2030 from $150-$180/kWh today.

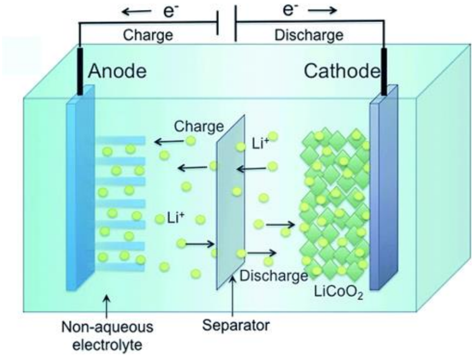

Figure 3. Lithium-Ion Battery Diagram

To reduce cost in the battery modules, battery cell and module manufacturers are increasing energy density and reducing quantities of expensive materials in the battery construction. At the system level, there are several opportunites for cost reduction including power covnersion, controls, and general EPC costs. Given its current capital and operating cost structure as well as the need to peridically replace energy capacity due to the annual degrdation rate, lithium-ion battery storage is generally limited to use cases and application that benefit from a relatively short duration, up to about 4 hours. Above 4 hours, lithium-ion battery system genrally become less economical. Typical use cases include TOU and demand charge management, load shaving, PV self-consumption, and backup power for behind the meter systems. For front of the meter systems, typical use cases include grid services (e.g. frequency regulation, voltage regulation, ramp rate control, etc.), timeshifting, energy arbitrage, and other ancillary services.

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[2] https://pubs.rsc.org/en/content/articlelanding/2017/ta/c7ta05283a#!divAbstract

Lithium-Ion Battery Storage: Cost & Performance Specifications	
Discharge Duration	1 - 8 hours
Capital Costs ($/kW; $/kWh) Forecasted Capital Costs (year 2030)	$900 – 1,700; $400 – 600 (2020) $450 – 900; $200 – $300 (2030)
O&M Costs ($/kW-year)	$10 – 20
Fuel Cost to Operate ($/kWh)	$0.08 – 0.09
Energy Capacity (based on existing installations)	Up to 5 MWh
Power Capability (based on existing installations)	>100 MW
Expected Life(1)	10 - 20 years (Energy augmentations can be performed at regular intervals to restore capacity to 100% of original)
Roundtrip Efficiency	85% (current leakage contributes to efficiency losses)
Energy Density (Wh/kg)	~210
Power Density (W/kg)	~2,000
Dispatch Response Time	milliseconds
Technology Applications	Grid frequency and voltage stabilization Demand response, ancillary services, backup power
Technology Drawbacks	Energy capacity degradation over time; safety concerns
Example Projects	Hornsdale, Australia (193.5 MWh / 150 MW)

1) The Li-Ion battery's relatively short lifetime and capacity degradation is often mitigated by energy capacity augmentation. Battery modules are added to the system at regularly scheduled intervals to restore the lost capacity.

4 Long Duration Energy Storage Technologies

Long-duration storage technologies can discharge for more than 4 hours, and provide different functionality compared to short-duration storage.

4.1 Redox Flow Battery

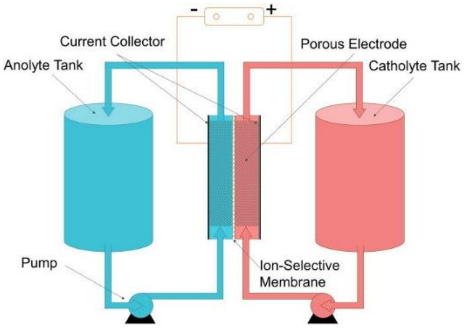

Figure 4. Redox Flow Battery Diagram

Flow batteries store energy via electro-chemical potential. Anolyte and catholyte aqueous solutions are stored in separate tanks. To discharge the battery, the solutions are pumped to a chamber divided by a semi-permeable membrane that allows electrons to flow between the anolyte to the catholyte, as shown in Figure 4.[3] This technology was introduced to the renewables market in the early 2000's and has seen varied interest over the years as various electrolyte compositions are explored. As with other storage technologies, interest has been piqued again in recent years with higher renewable market penetration and government subsidy, with several large-scale projects being planned. According to market research from 2018, the Flow battery market in 2023 is expected to be valued at more than 946 million (USD).

Redox Flow Battery: Cost & Performance Specifications	
Discharge Duration	4 - 12 hours
Capital Costs ($/kW; $/kWh)	$1,400 – 1,600; $250 – $350
O&M Costs ($/kW-year)	$10 - 12
Fuel Cost to Operate ($/kWh)	$0.08 - 0.11
Energy Capacity(1) (based on existing installations)	Up to 120 MWh (Capacity is directly related to amount of electrolyte and therefore can be easily increased)
Power Capability (based on existing installations)	>100 MW
Expected Life	5 - 10 years / ~12,000 cycles
Roundtrip Efficiency	65 - 85%
Energy Density (Wh/kg)	~35
Power Density (W/kg)	~166
Dispatch Response Time	milliseconds
Technology Applications	Grid frequency and voltage stabilization Peak shaving and baseload generation
Technology Drawbacks	Relatively low energy and power densities
Example Projects	Hokkaido Battery Storage Project (60 MWh / 15 MW)

1) Capacity of Flow batteries can be increased by adding electrolyte to tanks. This can also be used for energy capacity augmentation to restore capacity from degradation.

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[3] https://avs.scitation.org/doi/10.1116/1.4983210

Flow batteries systems are attractive due to their longer duration capabilities and long lifetime, reportedly able to operate for well over 10,000 cycles before exhibits energy capacity loss, compared to the few thousand cycles that lithium-ion batteries experience.

4.2 Underground Compressed Air to Power (CAES)

CAES plants store energy via compressed air. When power is inputted to the system, pumps send air into an underground chamber where the air becomes pressurized. Power is outputted by the pressurized air flowing out of the chamber and combusting with fuel to spin a turbine, as shown in Figure 5.[4] There are currently 2 active underground CAES projects, in Alabama and Germany, built in the late 1900's, that are primarily used for baseload generation. Large-scale renewable penetration has reignited interest in this storage technology, with several projects in discussion for the mid 2020's. Parallel with underground CAES is aboveground CAES, which allows for more flexible energy and power sizing by compressing air into aboveground tanks. This enables co-location with renewables and higher roundtrip efficiency. Several companies are currently investigating this technology

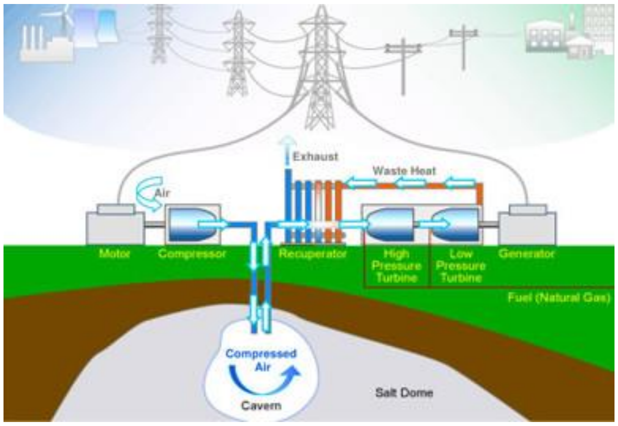

Figure 5. CAES Diagram

Underground Compressed Air to Power (CAES): Cost & Performance Specifications	
Discharge Duration	4 - 24 hours
Capital Costs ($/kW; $/kWh)	$1,000 – 1,200; $100 – $120
O&M Costs ($/kW-year)	$16 – 18
Fuel Cost to Operate ($/kWh)	$0.09 – 0.17
Energy Capacity (based on existing installations)	Up to 2,500 MWh
Power Capability (based on existing installations)	>100 MW
Expected Life	20 - 40 years
Roundtrip Efficiency	41 - 75%
Energy Density (Wh/L)	~12
Power Density (W/L)	~0.5
Dispatch Response Time	5 - 15 minutes
Technology Applications	Baseload generation and large-scale bulk energy storage Peak shaving and frequency/voltage regulation
Technology Drawbacks	Siting requirements can be inhibitive; high capacity floor
Example Projects	PowerSouth Energy Cooperative in Alabama

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[4] https://phys.org/news/2010-03-compressed-air-energy-storage-renewable.html

4.3 Pumped Hydroelectric Storage (Hydro)

Hydro plants store energy via the gravitational potential energy of water. Power inputted to the system pumps water from a lower elevation to a higher elevation. Power is outputted by water flowing back from the higher elevation to the lower elevation, spinning a turbine, as shown in Figure 6.[5] There have not been any Hydro systems constructed in the US since the 1980's, though there has been increased interest recently as more intermittent renewables have come online.

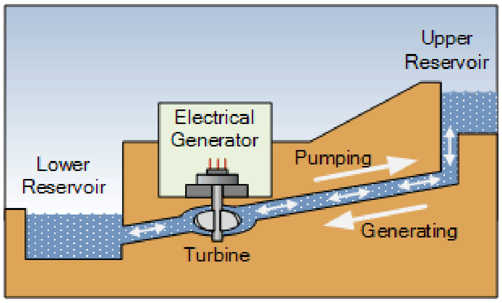

Figure 6. Pumped Hydro Storage Diagram

Pumped Hydroelectric Storage (Hydro): Cost & Performance Specifications	
Discharge Duration	6 - 24 hours
Capital Costs ($/kW; $/kWh)	$1,500 – 1,700; $150 – 180
O&M Costs ($/kW-year)	$13 – 17
Fuel Cost to Operate ($/kWh)	$0.08 - 0.09
Energy Capacity (based on existing installations)	Up to 40,000 MWh
Power Capability (based on existing installations)	4,000 MW
Expected Life	50 - 60 years
Roundtrip Efficiency	75 - 85% (evaporation contributes to efficiency losses)
Energy Density (Wh/L)	~2
Power Density (W/L)	~1.5
Dispatch Response Time	Seconds to Minutes
Technology Applications	Baseload generation and large-scale bulk energy storage Peak shaving and frequency/voltage regulation
Technology Drawbacks	Siting requirements and environmental concerns can be inhibitive (no new installations since 1980's); high capacity floor
Example Projects	Raccoon Mountain Pumped Hydro Plant (35.64 GWh / 1.62 GW)

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[5] https://www.alternative-energy-tutorials.com/energy-articles/pumped-hydro-storage.html

5 Gas-Fueled Technologies

Gas-fueled technologies can be used to perform the same functions as both short-and long-duration storage technologies, provided they can modulate their output as needed. A gas-fueled system that is operational can typically respond to grid signals to ramp up or down within milliseconds to seconds, providing a spinning reserve or demand response resource for the grid as loads from renewable resources change.

5.1 Industrial CHP

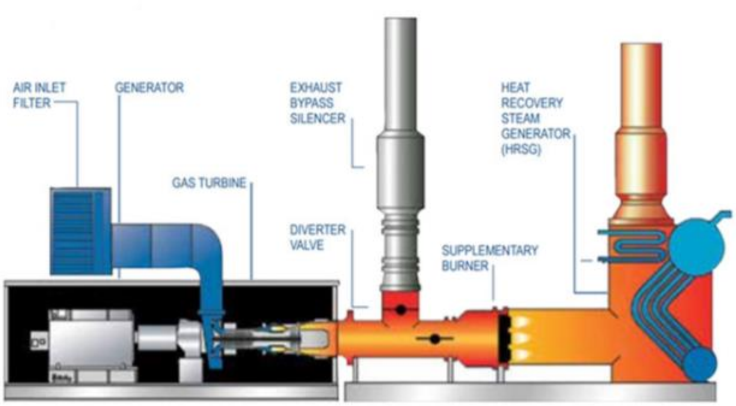

Figure 7. Industrial Gas Turbine Components

Industrial CHP systems have long been used in industrial manufacturing plants for electricity generation and steam that is used in manufacturing processes. Most industrial CHP systems are installed in facilities with significant steam and hot water requirements such as chemical plants or food processing facilities. In the past, electric utilities built cogeneration plants that produced steam for industrial facilities, and electricity for the power grid – more electricity than the facilities required. This practice is not as common now, but it could be adapted for new grid needs by deploying oversized CHP systems that communicate with the grid to provide services and modulate electricity production up and down as needed to balance renewable generation.

Flexible CHP systems with advanced controls to allow synchronous operation with the grid could offer a significant amount of power in high stress hours. These systems could also provide significant long-duration power as long as onsite thermal and electric needs are met.

Industrial CHP systems (engines and turbines >5 MW) generally cost between $1,200 and $1,800 per kW installed. But the *incremental* cost to upgrade to a larger CHP size – enabling flexible operation – can be significantly lower than the all-in cost on a per-kW basis.

Solar Turbines provided ICF with cost estimates for typical installations of their Taurus 70 and Titan 130 systems. The Taurus 70 has a capacity of 8 MW and the Titan 130 a capacity of 16 MW. Although the Titan is double the size, the installed cost is only 50% higher than the installed cost of the Taurus system. The larger CHP system will require more time to recoup the investment if there is not an opportunity respond to demand response events. However, if the growth of renewables enables increased monetization of demand response and ancillary service markets, the larger system may generate enough income to reduce their payback period.

As an alternative to oversizing, some CHP systems can produce more than their rated capacity for brief periods. Reciprocating engines can use inverters to “overclock” the engine for brief periods of time to increase capacity up to 30 percent. Gas turbines can increase combustion temperature to increase efficiency and rated capacity. While this functionality is limited to increasing output (rather than modulating up and down), it can be used to respond to under-production of electricity from renewable resources to maintain grid supply. Also, there is likely to be a slight increase in maintenance requirements for the systems depending on how often these tactics are deployed.

The incremental cost of additional capacity for flexible CHP operation is likely to be under $1,000/kW, and significantly less for the temporary capacity boosting options. However, the increases would be based on specific use cases, so the cost range for industrial CHP is given as $1,200-$1,800 per kW, based on the all-in cost of the system.

Industrial CHP: Cost & Performance Specifications	
Discharge Duration	>24 hours
Capital Costs ($/kW, $/kWh)	$1,200 – 1,800
O&M Costs ($/kW-year)	$30-45/kW-year (FOM), ~$10/MWh (VOM)
Fuel Cost to Operate ($/kWh)	$0.015 – 0.020, including thermal credit
Energy Capacity (based on existing installations)	~5,000 - 80,000 MWh (in addition to onsite generation)
Power Capability (based on existing installations)	~1-20 MW (in addition to onsite power generation)
Expected Life	15 - 20 years
Roundtrip Efficiency	Recip. Engine: 70-80%; Gas Turbine: 70-75% (CHP efficiency, HHV)
Dispatch Response Time	Milliseconds to seconds (depends on operational status)
Technology Applications	Baseload onsite generation, demand response, spinning reserve, other grid services
Technology Drawbacks	Engineering and design process can be complex
Example Projects	Bristol-Myers Squibb – Wallingford, CT (4.7 MW Gas Turbine)

5.2 Modular Gas Engines

Reciprocating engines fueled by natural gas are a mature technology, commonly used in both power generation and CHP applications. Modern reciprocating engines have high electric efficiencies, and relatively low installed costs. Engines have a faster ramp time compared to turbines, with the potential to respond to variable loads and participate in frequency regulation markets. A modular reciprocating engine power plant solution has been used in Texas and Kansas to balance variable loads from large wind farms. The Goodman Energy Center consists of 12 Wartsila 34SG engines for a total capacity of 104 MW.[6]

Figure 8. Reciprocating Engine Power Plant *(source: Wartsila)*

Portland General Electric (PGE) just installed a similar power plant with 220 MW of capacity from larger Wartsila 50SG engines. The plant is used to balance wind and solar energy, as well as provide load following and peaking services for PGE.[7]

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[6] https://www.wartsila.com/media/news/16-12-2014-wartsila-supplies-extension-to-a-wind-balancing-power-plant-in-kansas-usa

[7] https://www.windpowerengineering.com/wind-integrating-power-plant-supplied-wartsila-now-working-oregon/

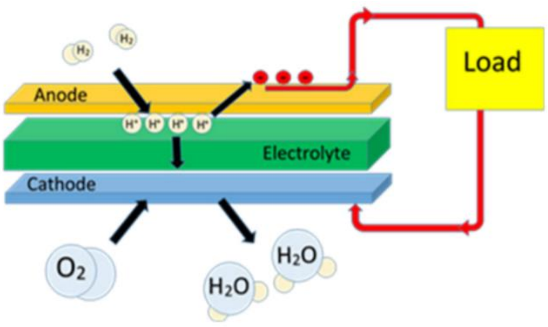
The advantage of modular power plants is that several engines can be operating near full capacity, while others operate in standby mode, with the potential to quickly ramp up production from several units simultaneously to meet variable output requirements. During periods of lower electric demand, individual engines can be disconnected for maintenance without any disruption to the operations or functionality of the plant.

Modular Gas Engines: Cost & Performance Specifications	
Discharge Duration	>24 hours
Capital Costs ($/kW, $/kWh)	$1,300 – 1,800
O&M Costs ($/kW-year)	$35/kW-year (FOM), ~$6/MWh (VOM)
Fuel Cost to Operate ($/kWh-year)	$0.03 - 0.05
Energy Capacity (based on existing installations)	20,000 – 40,000 MWh per engine
Power Capability (based on existing installations)	5 - 10 MW per engine
Expected Life	~30 years
Efficiency	36 – 42% (electrical efficiency, HHV)
Dispatch Response Time	Milliseconds to minutes (depends on operational status)
Technology Applications	Peak power, demand response, spinning reserve, grid support for variable loads
Technology Drawbacks	Relatively high maintenance, requires support to manage vibration
Example Projects	Goodman Energy Center, Kansas (104 MW, 12 engines)

While industrial CHP can be either customer-owned or utility-owned, modular engine power plants would be utility solutions, strictly providing electricity and associated services to the grid.

5.3 Power-to-Gas Fuel Cell (Electrolysis)

Both fuel cells and electrolysis technologies have been around for many years, but due to relatively high costs, they have not been widely deployed. Fuel cells extract electrons from hydrogen through electrochemical reactions, and hydrogen can be produced through electrolysis using water and an electric current. Fuel cell costs have been gradually declining for years, and power-to-gas fuel cells have started to gain attention as a way to utilize electricity from excess renewable generation.



When fuel cells operate on hydrogen, they produce zero emissions. But a hydrogen fuel supply is expensive, and not available in most locations, so most fuel cells use a reformer to convert natural gas into hydrogen, releasing some carbon emissions in the

Figure 9. Fuel Cell Diagram

process. However, hydrogen can be created with electricity and water through electrolysis. With an excess of renewable generation in the future, there could be opportunities to create hydrogen through electrolysis and use it in a fuel cell as needed. Alternatively, the hydrogen could be sold or used for other purposes. For example, hydrogen can be combined with carbon dioxide to produce a carbon-neutral methane fuel – renewable natural gas – that can replace natural gas in heating or CHP applications.

Hydrogen production through electrolysis will be another option to store renewable energy, effectively serving the same function as battery storage, although the round-trip efficiency is significantly reduced. Fuel cells with electrolysis equipment are also significantly more expensive than lithium-ion batteries.

Fuel Cell Power-to-Gas (Electrolysis): Cost & Performance Specifications	
Discharge Duration	Seconds - hours
Capital Costs ($/kW, $/kWh)	$2,900 – 5,600; $500 – 1000
O&M Costs ($/kW-year)	$30 – 40, plus stack replacement
Fuel Cost to Operate ($/kWh-year)	$0.03 – 0.04
Energy Capacity (based on existing installations)	Depends on electricity source and other sources of hydrogen
Power Capability (based on existing installations)	Up to 50 MW
Expected Life	10 – 30 years / ~20,000 cycles
Roundtrip Efficiency	34 – 51% (electrical efficiency, HHV)
Energy Density (Wh/kg)	~500 - 3,000
Power Density (W/kg)	~500
Dispatch Response Time	Seconds to minutes (depends on technology and operational status)
Technology Applications	Continuous power or CHP for microgrid, incorporating PV electricity for hydrogen production as available
Technology Drawbacks	Higher cost, lower efficiency than Li-Ion batteries
Example Projects	Maritime Hydrogen Fuel Cell Project

6 Technology Cost Comparison

Table 3 shows a summary of costs associated with each technology. Capital costs are presented on a per-kW basis. Operation and maintenance (O&M) costs are translated to dollars per kW per year. Finally, a "fuel cost to operate" figure is provided, which uses the 2019 EIA U.S. average industrial electricity and natural gas prices, combined with the range of system efficiencies, to estimate the cost to produce a kilowatt-hour of electricity. The Fuel Cost to Operate will vary depending on local electricity or gas prices, and whether or not the electricity can be obtained from excess renewable generation.

Table 3. Cost Comparison for Energy Storage Technologies

Technology	Primary Application	Capital Costs ($/kW)	O&M Costs ($/kW-year)	Fuel Cost to Operate ($/kWh)
Short-Duration Technologies				
Flywheel Energy Storage	Small-scale frequency and voltage stabilization	$2,000 – 4,000	$10 – 20	$0.08 – 0.10
Lithium-Ion Battery 2020	Small-to-large demand response, ancillary services, frequency/ voltage stabilization	$900 – 1,700	$10 – 20	$0.08 – 0.09
Lithium-Ion Battery 2030		$450 – 900	$5 – 10	$0.08 – 0.09
Long-Duration Technologies				
Redox Flow Battery	Industrial-scale peak shaving, frequency/ voltage stabilization	$1,400 – 1,600	$10 – 12	$0.08 – 0.11
Compressed Air to Power	Utility-scale baseload generation and peak shaving	$1,000 – 1,200	$16 – 18	$0.09 – 0.17
Pumped Hydro-electric Storage	Utility-scale baseload generation and peak shaving	$1,500 – 1,700	$13 – 17	$0.08 – 0.09
Gas-Fueled Technologies				
Industrial CHP	Industrial-scale demand response, spinning reserve	$1,200 – 1,800	$30-$45/kW-year, ~$10/MWh	$0.015 – 0.020
Modular Gas Engines	Demand response, spinning reserve, balancing renewables	$1,300 – 1,800	$35/kW-year, ~$6/MWh	$0.03 – 0.05
Power-to-Gas Fuel Cell	Convert excess electricity to hydrogen for time shifting	$2,900 – 5,600	$30 – 40/kW-year, plus stack replacement	$0.03 – 0.04

In order to compare total system costs, ICF assembled a 20-year life cycle cost comparison across all technologies using average values. We assume that equipment is installed in 2020, operating through 2040, at 2,000 full load equivalent hours of discharge/generation each year. Total estimated costs are assembled for each technology in 2020 dollars. The results are shown in Figure 10.

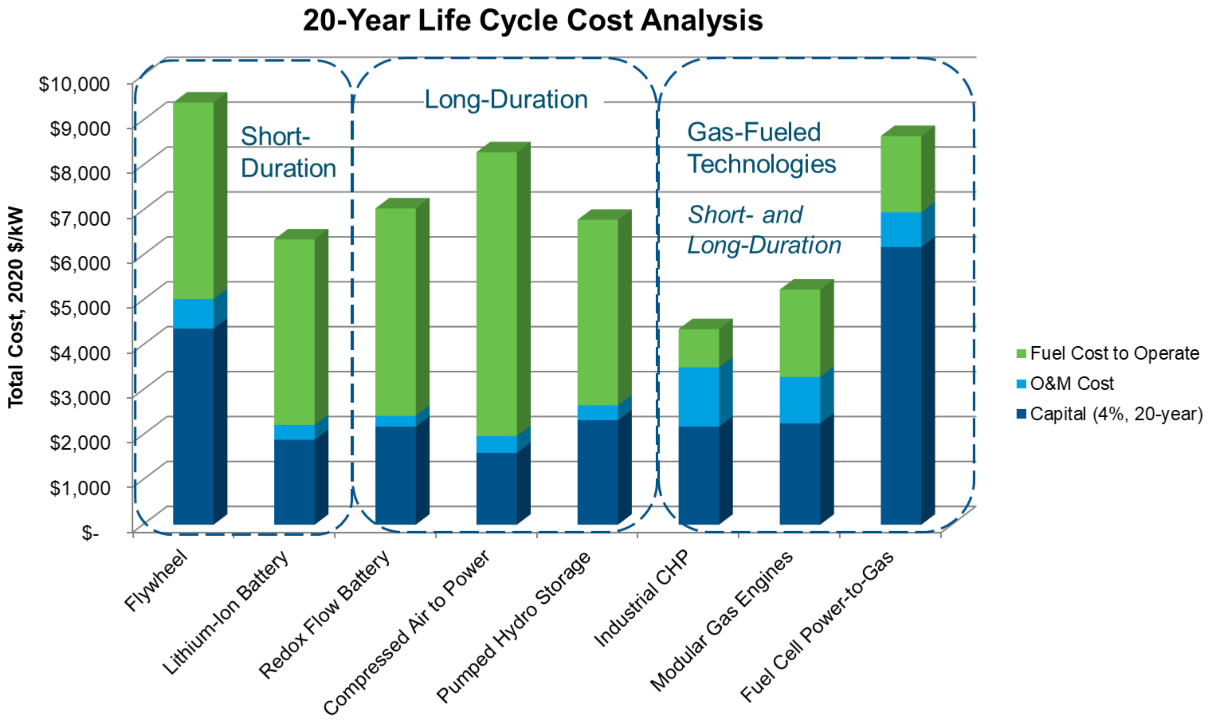


Figure 10. 20-Year Life Cycle Cost Comparison for Energy Storage and Gas-Fueled Technologies

Flywheels and Fuel Cell Power-to-Gas options represent the highest cost options, and the functionality of flywheels is somewhat limited. Compressed Air to Power and Pumped Hydro Storage opportunities were found to be limited based on land and space requirements. Thus, Lithium-Ion Batteries are the most promising technology for short-duration applications and Redox Flow Batteries are the most promising for long-duration storage requirements. However, gas-fueled technologies can fill many of the same roles, often at lower costs, and they tend to be overlooked when planning for additional renewable capacity.

When industrial CHP or modular gas engines can be utilized, they are likely to be more cost effective than Lithium-Ion or Redox Flow Batteries over a 20-year period, depending on storage requirements, local fuel costs, and available electricity markets.

7 Conclusions

As more variable renewable energy generation is incorporated into electric grids across the country, energy storage solutions will be required to respond to both short- and long-duration energy requirements, potentially including overnight or longer duration grid services that most current storage technologies cannot support. Lithium-ion batteries and other energy storage technologies will play a prominent role in providing some of these needs, but other fuel-based technologies could potentially be deployed in the same use cases, providing similar functionality.

For an industrial CHP system that has room to modulate electric loads and provide services to the grid, or a reciprocating engine power plant that can quickly ramp up and down, or a fuel cell that can incorporate electrolysis-produced hydrogen into its fuel supply, similar solutions can be provided as compared to other energy storage options while still supporting generation needs. Additionally, there are some limitations of electrically-charged energy storage – namely discharge duration limits, charging time requirements, and capacity degradation – that are not a factor for fueled options.

As shown in the comparison analysis, gas-fueled technologies are currently cost-competitive with other storage solutions. However, lithium-ion costs are projected to continue declining as manufacturing ramps up and technology improvements continue to be made, where 2030 prices for lithium-ion batteries are estimated to be half of 2020 levels. While gas-fueled options may no longer be cost-competitive for short-duration functions provided by Lithium-ion batteries at this point, there are several other functions that these technologies may provide to improve grid operations as more variable renewable energy generation comes online.

Moving forward, utilities and grid operators will need to determine which energy storage solutions will most cost-effectively meet their needs, while also weighing other factors like environmental goals and resiliency requirements for critical loads. In some cases, gas-fueled engines, turbines, and fuel cells may be able to provide many of the same functions as energy storage, in a way that provides benefits to both utilities and their customers.

8 Appendix

8.1 References

The data shown in this report are from a compilation of public sources and internal project experiences and assessments. The following are a list of public sources where data was obtained (in addition to Figure references).

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8.2 Definition of Terms

Flywheel: Flywheel energy storage systems use kinetic energy stored in a rotating mass. Power inputted to the system accelerates the mass via an integrated motor-generator. The kinetic energy of the rotating mass is expended via the same motor-generator to output power.

Industrial CHP: Gas turbine and reciprocating engine systems capable of providing both thermal energy to the host site, and electric power to the host site and the electric grid. The systems compared in this analysis range in size from 3.3 MW to greater than 20 MW.

Lithium-Ion Battery (“Li-Ion”): Li-Ion batteries store energy via electro-chemical potential. Lithium ions move through an electrolyte from the anode to the cathode when discharging, and vice-versa when charging.

Modular Fuel:

Power to Gas: Excess electricity can be used to convert water into hydrogen through the process of electrolysis. This fuel can then be used in a fuel cell system to produce electrical power.

Pumped Hydroelectric Storage (“Hydro”): Hydro plants store energy via the gravitational potential energy of water. Power inputted to the system pumps water from a lower elevation to a higher elevation. Power is outputted by water flowing back from the higher elevation to the lower elevation, spinning a turbine.

Redox Flow Battery (“Flow”): Flow batteries store energy via electro-chemical potential. Anolyte and catholyte aqueous solutions are stored in separate tanks. To discharge the battery, the solutions are pumped to a chamber divided by a semi-permeable membrane that allows electrons to flow from the anolyte to the catholyte.

Roundtrip Efficiency: The percentage of energy remaining after a charge/discharge cycle; generally measured from input and output of the storage system

Underground Compressed Air to Power (“CAES”): CAES plants store energy via compressed air. When power is inputted to the system, pumps send air into an underground chamber where the air becomes pressurized. Power is outputted by air flowing out of the chamber and combusting with fuel to spin a turbine.